Fast Time Structure During Transient Microwave Brightenings: Evidence for Nonthermal Processes

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ABSTRACT

Transient microwave brightenings (TMBs) are small-scale energy releases from the periphery of sunspot umbrae, with a flux density two orders of magnitude smaller than that from a typical flare. Gopalswamy et al (1994) first reported the detection of the TMBs and it was pointed out that the radio emission implied a region of very high magnetic field so that the emission mechanism has to be gyroresonance or nonthermal gyrosynchrotron, but not free-free emission. It was not possible to decide between gyroresonance and gyrosynchrotron processes because of the low time resolution (30 s) used in the data analysis. We have since performed a detailed analysis of the Very Large Array data with full time resolution (3.3 s) at two wavelengths (2 and 3.6 cm) and we can now adequately address the question of the emission mechanism of the TMBs. We find that nonthermal processes indeed take place during the TMBs. We present evidence for nonthermal emission in the form of temporal and spatial structure of the TMBs. The fast time structure cannot be explained by a thermodynamic cooling time and therefore requires a nonthermal process. Using the physical parameters obtained from X-ray and radio observations, we determine the magnetic field parameters of the loop and estimate the energy released during the TMBs. The impulsive components of TMBs imply an energy release rate of $\sim 1.3 \times 10^{22}$ erg s^{-1} so that the thermal energy content of the TMBs could be less than $\sim 10^{24}$ erg.

Subject headings: Sun: corona — Sun: flares — Sun: particle emission — Sun: radio radiation — Sun: sunspots — Sun: X-rays, gamma rays

1. Introduction

Transient microwave brightenings (TMBs) are small-scale energy releases in coronal active regions, first detected by Gopalswamy et al (1994) using the Very Large Array[1] (VLA) at 2 cm wavelength. The TMBs are compact (∼2 arc sec) sources with duration ranging from less than a minute to more than 20 minutes. The typical microwave flux of the TMBs at 2 cm is nearly two orders of magnitude smaller than that from normal flares. The TMBs are also highly polarized, sometimes reaching 100%; they are located close to the spotward footpoints of coronal loops connecting the periphery of the sunspot umbra to nearby regions of opposite magnetic polarity. Gopalswamy et al. (1994, hereafter referred to as Paper 1) interpreted the TMBs as the radio signatures of small scale heating and/or particle acceleration in compact magnetic flux tubes where the magnetic field is 1200-1800 G. When the microwave observations overlapped with soft X-ray observations some TMBs were found to show X-ray signatures similar to the ones first reported by Shimizu et al (1992, 1994). Recently, Shibasaki (1996) reported such radio brightenings above a large sunspot, although his events are brighter by an order of magnitude than those reported by us. In Paper 1, the brightness temperature and polarization of the TMBs were found to be consistent with either thermal gyroresonance emission or nonthermal gyrosynchrotron emission, but not with thermal free-free emission. In this letter, we present evidence for both thermal and nonthermal processes during the TMBs based on their temporal and spatial evolution.

[1]The Very Large Array is a facility of the National Radioastronomy Observatory, which is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

2. Data and Results

The TMBs occurred in the vicinity of a large sunspot in AR 7135 (S16W14 at 0 UT on 1992 April 24). Observations were made at several wavelengths sequentially. In Paper 1, a detailed description of the VLA observations can be found. We have analyzed these 2 cm observations with full time resolution (3.3 s) and extended the analysis to 3.6 cm wavelength. The resulting radio images have a spatial resolution of $\sim 2''$ at 2 cm and $\sim 3''$ at 3.6 cm. Figure 1 shows the superposition of radio contours on the optical image of the sunspot obtained by the SXT aspect sensor on the Yohkoh spacecraft (Tsuneta et al, 1991). The extended emission is the gyroresonance emission from the sunspot itself. The compact source to the south-east is the TMB. In Fig. 2 we have shown another TMB at 2 cm from a different location, to the south-west of the sunspot. The 3.6 cm data have confirmed the results of Paper 1 that the TMBs occur frequently, close to the sunspots. The brightness temperature of the TMBs was up to several MK at 3.6 cm and up to 1 MK at 2 cm. In all, about two dozen TMBs were observed. Here, we consider only 5 TMBs which form a representative sample of all the TMBs. Table 1 lists the properties of the TMBs.

2.1. Time Structure of TMBs

In Fig. 3, we have plotted the intensity at the brightest pixel of each TMB listed in Table 1. The time profiles fall into three catagories: impulsive (I) (Fig. 3a,b), mixed (I+G) (Fig. 3c,d) and gradual (G) (Fig. 3e) events.

Gradual Events: The time profiles of gradual events are similar to the gradual rise and fall (GRF) events well known during normal flares, but of smaller flux and an overall lifetime exceeding ~ 1 min. Fig. 3e is the smooth profile of a gradual event starting around 15:39 UT on 1992 April 24. The flux gradually increases by a factor of 3 over a period

of several minutes. The TMB was still in progress when the observation ended at 3.6 cm wavelength. When the observation resumed at 3.6 cm an hour later, the gradual TMB was gone.

Impulsive Events: The impulsive TMBs are very short in overall lifetime, typically about a minute. The rise time is of the order of the time resolution of the observation. The decay time is relatively longer, but this is probably due to the presence of a gradual component much weaker than the impulsive peak. In Fig. 3a,b we have shown two examples of the impulsive events: the 22:16 UT event at 2 cm and the 20:12 UT event at 3.6 cm. The two events occurred at completely different positions with respect to the sunspot and had an FWHM of only 10 and 5 s respectively. The total duration of the TMB was less than 2 min in both cases.

Mixed Events: Some TMBs consist of two time scales corresponding to the gradual and impulsive components. We refer to these as mixed events. In Fig. 3c,d we have presented the time profiles of two TMBs with superposed gradual and impulsive components. The time structure (with 30 s time resolution) in the 16:24 UT event was already noted in Paper 1. With 3.3 s time resolution, we find that several short time-scale structures are superposed on the relatively intense gradual component. This TMB was of sufficiently long duration that it continued into the subsequent 3.6 cm observation and showed similar time structure (not shown). The impulsive components are seen as modulations on the gradual profile. The FWHMs of these impulsive components were again $\sim$ 5-10 s. The 18:54 UT event at 3.6 cm is somewhat different in that the impulsive components preceded the gradual components as in regular flares. The TMB consists of three spikes each with a FWHM of $\sim$ 5-10 s, followed by a gradual component which lasted for more than 2 min. The gradual component itself was superposed by two spikes, each with a duration of $\sim$ 5 s.

2.2. Spatial Structure and Polarization

We compared the spatial structure and polarization of the TMB source during impulsive and gradual components. Figure 4 shows the source structure of two TMBs during the impulsive and gradual phases. The 20:18 UT TMB is impulsive, with an extremely weak gradual component while the 18:53 UT event has both gradual and impulsive components of comparable brightness (see Fig. 3a,c for the time profiles of these two events). We see that the radio source is rather elongated in one direction during the impulsive component. We also note that the elongation is in the direction of the magnetic loop seen in X-rays as was shown in Paper 1. However, in the decay phase, when the impulsive component declined, the source becomes somewhat compact.

Both the impulsive and gradual components are right hand circularly polarized. Since the sunspot is of positive polarity, both the impulsive and gradual components have dominant extraordinary mode. The degree of polarization of the gradual components (shown in parentheses in the last column of Table 1) is somewhat larger than that of the impulsive components during any given TMB. This is also true when we compare impulsive and gradual events. The difference in polarization between the impulsive and gradual components is largest during the 16:24 UT event (88% for the gradual component and 53% for the impulsive component).

3. Interpretation

We interpret the observed time structure as indicative of both thermal and nonthermal processes during TMBs. The gradual components represent energy release in the form of heating while the impulsive components indicate acceleration of energetic electrons. The time scale of the gradual component is consistent with typical cooling times of coronal

loops. However, fast time structures cannot be explained by a thermal process because the cooling time (τ_c) is usually an order of magnitude larger than the FWHM of the impulsive components. The cooling time (in seconds) in coronal loops is given by (Serio et al, 1991),

$$\tau_c = 120 L_9 T_7^{-0.5}, \tag{1}$$

where L_9 is the loop half-length in units of 10^9 cm and T_7 is the temperature of the loop in units of 10^7 K. Almost all the TMBs discussed in this paper came from one footpoint of a single magnetic loop structure which had a typical half-length of $\sim 1.2 \times 10^9$ cm. The temperature of the loop was obtained from soft X-ray observations as ~ 5 MK. The resulting cooling time is 204 s which is 40 times larger than the FWHM of the impulsive components. Since τ_c scales linearly with the loop length for a given temperature, we need a loop length much less than an arc sec if the fast time structure were to be explained by cooling.

Since the TMBs are located in the vicinity of a large sunspot, the magnetic field is expected to be very high and is expected to play an essential role in the emission process. The relevant thermal emission process for the gradual component is gyroresonance emission, since the free-free emissionis negligible as shown in Paper 1. The thermal gyroresonance emission is also consistent with the high degree of polarization of the gradual component. For the 2 cm emission, the relevant gyroharmonic number is 3, corresponding to a magnetic field of 1800 G. This is also suggested by the compact source structure observed for the gradual components.

For the impulsive components, the relevant emission mechanism is optically thin gyrosynchrotron emission from nonthermal electrons. In order to explain the fast time structure, the nonthermal particles must have a lifetime similar to the duration of the impulsive components. The lifetime of nonthermal particles in a coronal loop is determined

by the collisional damping time (τ_l):

$$\tau_l = 2 \times 10^8 n^{-1} E^{3/2} \tag{2}$$

where E is the energy (in units of keV) of the nonthermal particles and n (in units of cm^{-3}) is the thermal electron density in the coronal loop. We again make use of the density of the loop ($\sim 5\times 10^9$ cm^{-3}) obtained from soft X-ray observations reported in Paper 1. In order to account for the observed duration ($\tau_l = 5 - 10$ s) of the impulsive components, we need nonthermal particles in the energy range $10 - 20$ keV. It is significant to note that this is the energy range of nonthermal electrons involved in the production of weak metric type III radio bursts (e.g., Lin et al 1981). If higher energy electrons are produced, all of them have to escape from the loop in order to be consistent with the duration of the impulsive components.

Gyrosynchrotron emission from such low energy electrons can occur only at the first few harmonics of the gyrofrequency. At 2 cm, the relevant harmonics are 3 to 5 corresponding to a field of 1800 to 1070 G along the loop. We have excluded harmonic 2 which would need magnetic fields higher than indicated by observations. For 3.6 cm emission, the relevant harmonics are 2 to 4, corresponding to field strengths in the range 1500 to 1000 G. The brightness temperature contribution at harmonics higher than 5 is negligible. Thus one expects nonthermal microwave flux from the section of the coronal loop where the magnetic field is 1800 to 1000 G. This is why we see the elongation of the source for the impulsive components. This is in contrast to the gyroresonance source for which the (optically thick) emission comes from a single harmonic. For TMBs with impulsive and gradual components, the lowest harmonic emission consists of contributions from both thermal and nonthermal processes.

Since the spotward leg of the magnetic loop has a high magnetic field and the opposite leg connects to a region of very low photospheric field, one expects a rapid decline of the

magnetic field with distance away from the spot. We can determine the magnetic field gradient in the region of 3.6 cm emission as ~ 0.1 G km^{-1}, corresponding to a magnetic field change from 1500 G to 1000 G over a distance of about $6.7''$ (see Table 1) along the loop. This is consistent with the values computed from thermal gyroresonance emission of a TMB observed at 2 and 3.6 cm (Zhang et al 1997).

The 3.6 cm peak brightness temperature ($>$ 10 MK) of the TMB at 20:12 UT (see Table 1) is further evidence for nonthermal emission: the electron temperature of the coronal loop in which the TMB occurred is only about 5 MK. Unfortunately, there was no X-ray observation at the precise moment of the TMB although the temperature was measured a few minutes before and after the TMB.

4. Discussion and Conclusions

We have presented evidence for nonthermal radio emission during TMBs, in addition to thermal emission. The nonthermal radio emission is from energetic electrons with energy around 10-20 keV. For both thermal and nonthermal emissions reported in this paper, the existence of a strong magnetic field is an important factor permitting gyrosynchrotron and thermal gyroresonance emissions at low harmonics. In this respect, these TMBs are unique and are confined to the neighborhood of large sunspots. The typical 2 cm microwave flux due to free-free emission from the magnetic loop in question is insignificant. In another study, White et al. (1995) searched for the radio signatures of four X-ray transient brightenings and found that the time profiles in X-rays and radio were similar, suggesting plasma heating rather than particle acceleration. It must be pointed out that the events studied by White et al. did not originate from the neighborhood of large sunspots. It may be hard to detect nonthermal microwave emission from 10 keV electrons in coronal loops away from the sunspot (where the magnetic field is low) due to the following reason:

microwave flux due to thermal gyroresonance and nonthermal gyrosynchrotron flux is insignificant at harmonics above the first few, but the low magnetic field means the emission has to be at high gyroharmonics (harmonic number 27 is needed for emission at 2 cm in a field of 200 G). Our conclusion is consistent with the fact that nonthermal hard X-rays in the energy range 7-10 keV were detected by CGRO/BATSE (Feffer, Lin & Schwartz, 1996). We predict that BATSE spectroscopy detectors will be able to detect nonthermal processes in TMBs close to and away from sunspots while microwave instruments can detect only close to the sunspot. Thus lack of nonthermal radio emission from regions away from the sunspot does not mean that the energy release is purely thermal.

Recently, Gary et al. (1997) studied a larger sample of TMBs using Owen's Valley Radio Observatory (OVRO) data at many frequencies in the range 1-18 GHz. Taking advantage of the multifrequency observations, they determined the spectra of the TMBs and found that some of them did have nonthermal spectra. Unfortunately, imaging of the TMBs was not possible using the OVRO Solar Array and we do not know the location of the TMBs with respect to the soft X-ray sources.

The finding that many of the TMBs contain a nonthermal component also raises an important question whether counting just the thermal signature such as the soft X-ray brightenings is adequate to decide the contribution of these small-scale releases to the coronal heating. If the released energy goes predominantly into nonthermal particles which in turn lose their energy to the coronal loop, we may be undercounting the number of energy input episodes to the coronal loops. Indeed, it was shown by Peres et al. (1992) that a coronal loop can be maintained at a steady temperature, provided the time interval between two successive energy inputs is less than the cooling time, which is typically a few minutes as given by equation (1).

The typical energy released during a nonthermal pulse can be calculated as follows.

The volume of the loop determined from X-ray observations is $\sim 2\times 10^{26}$ cm^3. Using the required nonthermal (20 keV) particle density of $\sim 5\times 10^3$ cm^{-3}, we get the total energy released during a nonthermal spike as 6.4×10^{22} erg, with an energy release rate at least 1.3×10^{22} erg s^{-1}. If all the nonthermal electrons lose their energy to the coronal loop, then the thermal energy content of the TMBs can be determined from the energy release rate. For example, the short duration TMBs lasting for about a minute would carry a thermal energy content of $\sim 7.8 \times 10^{23}$ erg. This is over an order of magnitude smaller than the thermal energy content (10^{25} erg) of a typical soft X-ray brightening. On the other hand, the longer duration TMBs, such as the 16:24 UT event in Table 1, would have a thermal energy content of $\sim 10^{25}$ erg. Thus radio observations indicate energy releases much lower than what is found from X-ray observations. The TMBs, therefore, seem to be good examples of Parker (1988) nanoflares and hence may be important in heating at least certain regions of the solar corona. It is unclear how the energy is actually released and distributed between particle acceleration and heating during these energy release episodes at the smallest scales. This question arises because some of the TMBs do not seem to have a gradual component. In order to fully understand this question, we need simultaneous radio and X-ray observations with sufficiently high spatial and temporal resolution.

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Table 1. Properties of Transient Microwave Brightenings

UT range 1992 Apr 24	λ (cm)	Gradual or Impulsive	τ_{spike} (sec)	τ_{TMB} (min)	beam size ($arcsec^2$)	source size ($arcsec^2$)	Flux (SFU)	T_b (MK)	polarization (%)
$15:39-15:49$	3.6	G	–	> 8	3.9×2.8	5.3× 3.4	0.14	1.3	(62)
$16:24-16:44$	2.0	$I+G$	10	14.0	2.0×1.5	2.4×1.8	0.033	0.4	53(88)
$18:38-18:56$	3.6	$I+G$	5	3.0	3.0×2.5	3.9× 2.8	0.15	2.4	46(51)
$20:12-20:30$	3.6	$I+G$	5	2.0	3.0×2.6	6.7× 3.5	1.38	10.2	33(53)
$22:04-22:09$	2.0	I	10	1.5	2.0×1.5	2.8 ×1.6	0.026	0.3	59

λ: Observing wavelength; G: Gradual; I: Impulsive; τ_{spike}: Duration I component; τ_{TMB}: Duration of TMB

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Fig. 1.— Overlay of the microwave (VLA 3.6 cm) contours on the image of the large sunspot from AR 7135 on 1992 April 24. The sunspot image was obtained by the SXT aspect sensor; the bright ring structure near the umbra is an artifact because what is displayed is the low 8 bits of the 12-bit image. The compact source to the south-east (indicated by the arrow) is the TMB at 16:34 UT. North is to the top and east is to the left. The extended radio contours correspond to the sunspot associated microwave emission which is shifted slightly to the south-west of the spot because of its height in the corona and the angular dependence of gyroresonance emission; the location of the spot is S16W25. 10, 20, 30, 40, 50, 60, 70, 80, 90, 99% of the peak intensity (.0627 sfu/beam); beam size is $3'' \times 2.5''$.

Fig. 2.— Overlay of the microwave (2 cm) contours on the sunspot image for the 1992 April 24 22:04 UT TMB (indicated by the arrow mark) which occurred to the south-west of the sunspot. The sunspot is again obtained by the SXT aspect sensor with similar artifact as in Fig. 1. North is to the top and east is to the left. The sunspot associated emission at 2 cm occupies a small south-west section of the umbra. The radio contours are at 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, 99% of the peak intensity (.02496 sfu/beam); beam size is $2'' \times 1.5''$.

Fig. 3.— Microwave time structure of the five TMBs observed on 1992 April 24. (a) the 22:16 UT TMB at 2 cm and (b) the 20:18 UT TMB at 3.6 cm which are purely impulsive. (c) the 18:54 UT TMB at 3.6 cm has impulsive components preceding the gradual component. (d) the 16:24 UT TMB at 2 cm has a dominant gradual component with superposed impulsive components. (e) the 15:39 UT TMB at 3.6 cm is a purely gradual event with no significant impulsive component.

Fig. 4.— Radio images of two TMBs observed on 1992 April 24 in contour representation. The left (right) panel corresponds to the impulsive (gradual) component. Note that the source is more elongated for the impulsive component. The peak flux of each image and the image time are marked on the left hand top corner of each panel. The contour levels are at

5, 10, 15, 20, 25, 30, 40, 50, 75, 100, 150, 200 milli sfu/beam. The X and Y axes are in pixel units (pixel = 0.6 arcsec at 3.6 cm).